THE PLANET COLLABORATION: Probing Lensing Anomalies

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Abstract

The Probing Lensing Anomalies NETwork (PLANET) is a worldwide collaboration of astronomers using semi-dedicated European, South African, and Australian telescopes to perform continuous, rapid and precise multi-band CCD photometric monitoring of on-going Galactic microlensing events. As well as providing important additional information on the nature, distribution and kinematics of Galactic microlenses, PLANET photometry is optimized for the detection of Jovian-mass planets orbiting several AU from Galactic lenses. The final PLANET database is expected to contain hundreds of variable stars sampled at hourly time scales with 1-5% precision.

1 The PLANET Collaboration

The massive observing programs launched in the early 1990s to detect the transitory microlensing of background sources in the Magellanic Clouds and Galactic bulge by (moving) foreground stars or dark lenses in the Milky Way are now bearing fruit (DUO [1], EROS [5]; MACHO [4]; and OGLE [16]). More than 100 microlensing events by compact objects in the Galaxy have been reported in the literature so far. It has proved possible to distinguish the standard microlensing light curve, which assumes that a point-source undergoes amplification by a point lens with relative rectilinear motion, from those of other forms of stellar variability. Unfortunately, the Einstein ring crossing time, a degenerate combination of the lens mass, and the geometry and kinematics of the source-lens-observer system, is

the only fitting parameter of the standard curve that contains information about the lensing system. In order to learn more about the microlenses, information must be gleaned from the "anomalous" fine structure in the light curves caused by departures from the standard assumptions. Reliable detection of most of these anomalies requires more frequent and precise monitoring than that performed by the current survey teams.

PLANET (**P**robing **L**ensing **A**nomalies **NET**work) is a worldwide collaboration of astronomers with access to a network of European, South African, and Australian telescopes [3] designed to meet the challenge of microlensing monitoring. The primary goal of PLANET is the detection and characterization of the lensing *anomalies* that are expected in the presence of binary sources, binary lenses, blending, parallax effects due to the Earth's motion, and finite source size effects. In particular, since the presence of a lens with a planetary system can create a detectable perturbation lasting a few hours to a few days, intensive microlensing monitoring is a powerful method for the detection of extrasolar planets at kiloparsec distances. Secondary goals include the search for serendipitous microlensing events in PLANET monitoring fields, and galactic structure and variable star studies.

2 The 1995 Pilot Season

In its 1995 pilot campaign, PLANET had dedicated access to four southern telescopes in June-July 1995: (1) the ESO/Dutch 0.92m on LaSilla, Chile, (2) the Bochum 0.6m also on LaSilla, (3) the South African Astronomical Observatory (SAAO) 1.0m at Sutherland, South Africa, and (4) the Perth Observatory 0.6m at Bickley in Western Australia. The longitude coverage of PLANET telescopes not only acted as a hedge against bad weather, but also increased the chances of detecting short-term anomalies of the sort expected for planetary events and caustic crossings, and allowed independent checks on any observed anomaly from another site. With the addition of the Canopus 1m in Tasmania, PLANET has expanded its longitude coverage for the 1996 season, which is now in progress.

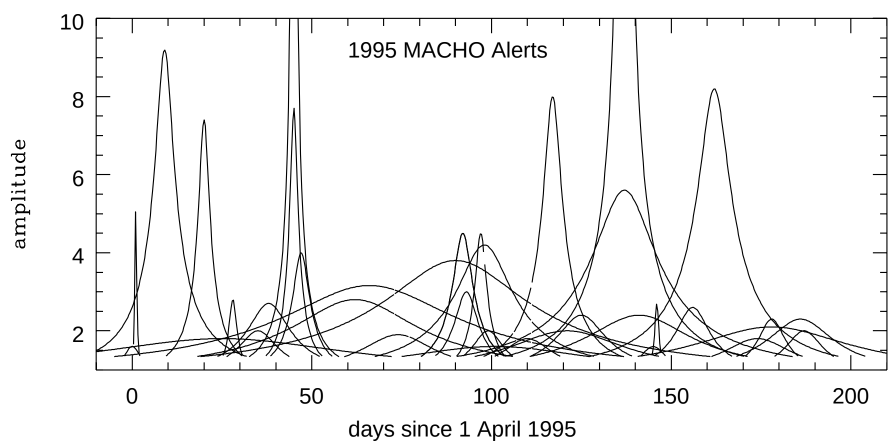

Fig. 1: Light curves for the 1995 real-time electronic alerts given by MACHO; parameters are from their alert page at http://darkstar.astro.washington.edu. The 1995 PLANET pilot season corresponded to days 73-111.

The alert capability of OGLE [17] and MACHO [14], which allows them to detect and electronically report on-going microlensing events in real-time, has enabled PLANET to use its small fields of view ($\sim 4'$) to best advantage, by concentrating on monitoring events already known to be in progress. The EROS II collaboration plans to give alerts in the 1997 bulge season. The number of 1995 alerts assured that PLANET telescopes were kept busy whenever the bulge was visible; the majority of on-going events that coincided with the pilot campaign were monitored (Fig. 1).

Microlensing detection teams typically sample a field once a night and thus produce light curves that are well-sampled on the 10 — 100 day time scales expected for lenses with $0.1 \lesssim M \lesssim 1\ \mathrm{M}_\odot$ with photometric precision of about 0.25 mag at V=20 (I=18.5) (Cook, these proceedings). Analysis of the 1995 pilot data has indicated that PLANET telescopes can be continuously and fruitfully employed

throughout the bulge season performing photometry beyond the reach of the microlensing survey teams providing the alerts: PLANET photometry is >10 times more frequent (Fig. 2) and and ∼5 times more precise (Fig. 3) than that of the MACHO team, for example.

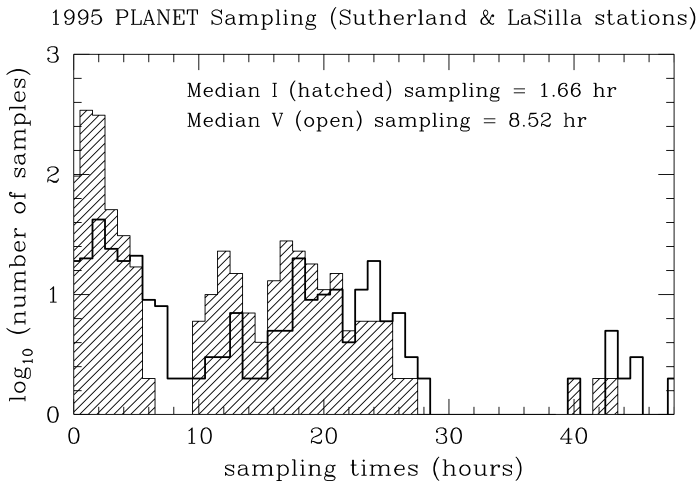

Fig. 2: Histogram on a logarithmic scale showing the time between PLANET photometric measurements in 1995 for Sutherland (SAAO) and LaSilla stations combined in the I (hatched) and V (open) bands.

Relative crowded-field photometry was performed to I≈19.5 (V≈21) using a set of 10 secondary standards in each field that were calibrated during the run. Exposure times were adjusted to obtain comparable errors in I and V. Using 1m class telescopes, relative 1%, 2% and 6-7% photometry was obtained at I=15, I=17 and I=19 respectively, and was limited by crowding, not photon noise. The binarity of MB9512, one of the seven events monitored intensively in the 1995 campaign, was discovered in real time with PLANET mountain-top reduction. Final DoPhot [15] reduction yielded the light curve shown in Fig. 4. The 1995 data are now fully reduced; a paper is in preparation.

Fig. 3: Formal DoPhot error as a function of I-band magnitude for one $4'$ PLANET (LaSilla) field taken in $1.5''$ seeing. The number of stars and median error (mags) in each magnitude bin is given above that bin. *Top:* Only stars with well-measured point spread functions are shown. *Bottom:* All measured stars are plotted.

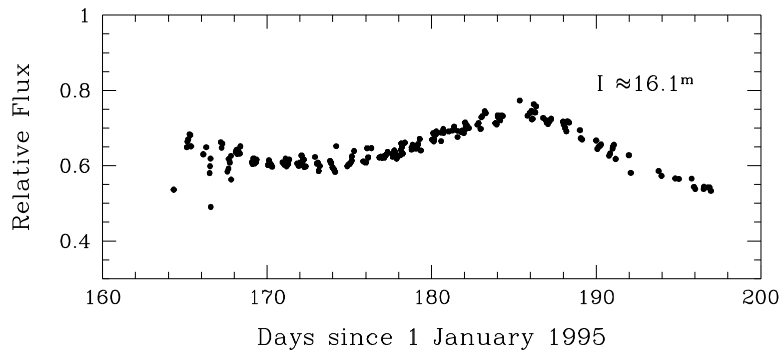

Fig. 4: The relative flux of MB9512 in arbitrary units. About 200 *unaveraged* points from three sites are plotted to indicate the true scatter. Higher scatter in the first nights is due to poor seeing and high background.

3 Astrophysical Returns of PLANET Monitoring

The primary goal of PLANET is the detection of microlensing anomalies that will enable the characterization of Galactic microlenses and their sources, and the detection and characterization of extra-solar planets. Multiple lenses create caustics that result in sharp enhancements with durations as short as a few hours. The resolution of these caustic crossings would more tightly *constrain the distribution of binary masses and separations* in the Galactic disk and bulge [11].

A special case of a binary is a lens with a planetary system. A planet in the "lensing zone" (1-6 AU for most lenses) with a planetary Einstein ring that does not resolve the source, will create sharp caustic structure in the light curve with durations of a few hours to a few days [12]. Photometry capable of characterizing 4-5% deviations would result in detection probabilities near 15-20% for Jupiter-mass planets in the lensing zone [9]. If extra-solar planetary systems are common, precise microlensing monitoring can produce *distributions of planet-lens mass ratios and reduced projected orbital radii for planets around randomly-selected stars at kiloparsec distances from Earth.* On the other hand, non-detection of planetary lensing anomalies would place strong constraints on Jupiter- to Neptune-mass planets, if $\sim$100 events can be monitored with sufficient precision and sampling. The caustic structure of Earth-mass planets would resolve giant sources, resulting in only a fraction of the source being amplified and a severe reduction in the size and chance of a planetary perturbation [6]. Reliable detection of Earth-mass planets requires characterization of 1-2% deviations against non-giant sources for hundreds of events.

PLANET's photometry is much more suited than that of the microlensing surveys to the detection of color-shifts due to blended light from chance superpositions [2] or from the lens itself [7]. Measuring blending produces *more accurate time scales for microlensing events* and *constrains the mass of stellar lenses*. The non-rectilinear motion of the Earth around the Sun causes a parallax-shift in every event that in principle can be used to extract *kinematical information about the lens*, but hourly sampling and $\sim$1% photometry are required to achieve a 10% detection rate [8]. Lensing of giants at small impact parameter will resolve the source star structure, producing a chromatic signal of 2-4% at V-I due to limb-darkening. Detection of this small chromatic signal over the few hours of the transit would provide *a test of model atmospheres for giants* [10]. In addition, since the physical size of the source can be determined, source resolution yields the transit time and thus *the proper motion of the lens*, if the light curve is well-sampled over its peak with small photometric error [13].

In addition to the characterization of lensing anomalies that result from rapid, precise measurements of the microlensing event in each PLANET field, a large database of magnitudes and colors will be generated for the other 6,000 - 10,000 stars in each field. In particular, the PLANET database is especially well-suited to the *study of short-period, low-amplitude variables* (Fig. 5). Variables with sub-day periods have been discovered in the pilot season data. Furthermore, since PLANET monitors

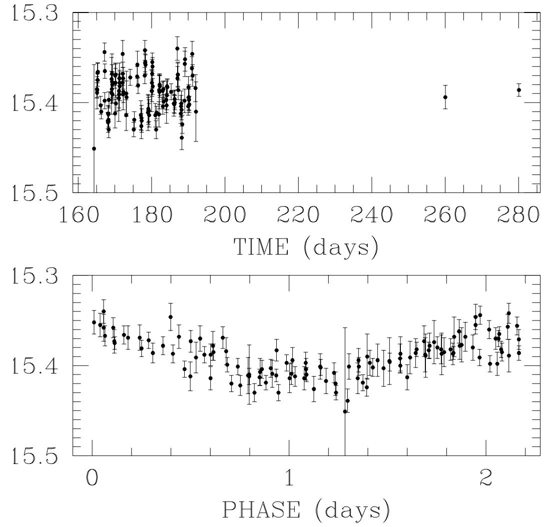

Fig. 5: *Left:* The (LaSilla) I-band light curve of a variable found in one of the PLANET fields is shown in the top panel and is phase-wrapped in the bottom panel to reveal its 2-day period and peak-to-trough amplitude of ∼0.05 mag. *Right:* A PLANET color-magnitude diagram containing ∼5000 stars for an OGLE-alerted field.

in standard V and I filters, precise color-magnitude diagrams (CMD) can be built for fields scattered throughout the bulge, and the morphology of the CMD along different lines of sight utilized to disentangle the *effects of differential extinction* from those resulting from *Galactic structure*.

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